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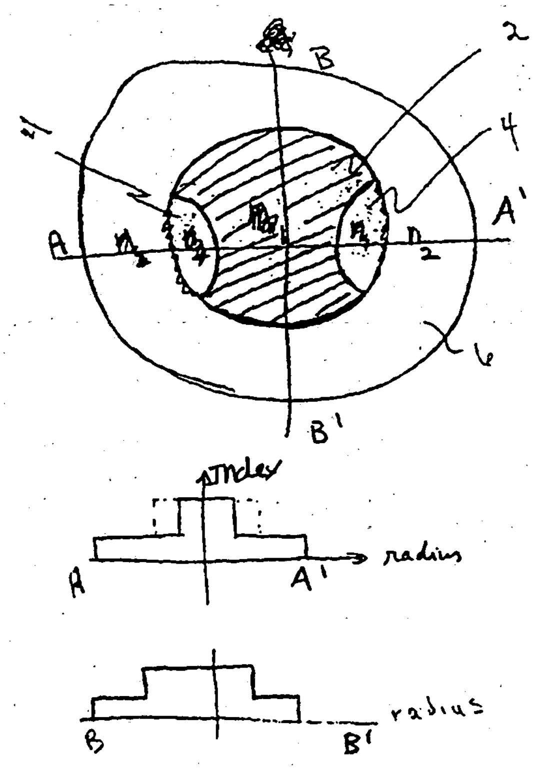
(54) Title: RADIALLY NON UNIFORM AND AZIMUTHALLY ASYMMETRIC OPTICAL WAVEGUIDE FIBER

(57) Abstract

Disclosed is a single mode waveguide fiber and a method of making a single mode or multimode waveguide fiber which has an azimuthally and radially asymmetric core. This asymmetry provides additional degrees of freedom for use in forming a waveguide having particular performance characteristics.



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RADIALLY NON UNIFORM AND AZIMUTHALLY ASYMMETRIC OPTICAL WAVEGUIDE FIBER

BACKGROUND OF THE INVENTION

This application is based upon the provisional application S.N. 60/099,535, filed 9/9/98, which we claim as the priority date of this application.

The invention relates to an optical waveguide fiber and a method of making a waveguide fiber, having a refractive index profile which varies in both the radial and azimuthal directions. The additional flexibility afforded by the azimuthal variation provides for index profile designs which meet a larger number of waveguide fiber performance requirements than is possible using refractive index variation in only the radial coordinate direction.

Recent development of waveguide fibers having refractive index profiles which vary in the radial direction has shown that particular properties of the waveguide can be optimized by adjusting this profile. Varying the refractive index profile in a more general way than, for example, a simple step, allows one to select the value of one or more waveguide properties without sacrificing a base set of properties including attenuation, strength, or bend resistance.

In addition, certain azimuthal asymmetric core refractive index profiles, such as those having elliptical, triangular, or square core geometry have been shown to provide useful waveguide properties such as preservation or mixing of the polarization modes.

It is expected, therefore, that core refractive index profiles which vary in both the azimuthal and radial direction will offer the opportunity to fabricate waveguides having new or improved properties for use in telecommunication, signal processing, or sensor systems.

In U. S. patent 3,909,110, Marcuse, ('110 patent) an azimuthally asymmetric core of a multimode waveguide is described. A calculation in the '110 patent indicates that periodic variations in index in both the radial and azimuthal directions would cause mode coupling, thereby increasing bandwidth, while limiting losses due to coupling to radiation modes. The concept was not extended to include single mode waveguides. Also the scope of the '110 patent is quite limited in that it refers only to sinusoidal azimuthal variations.

In describing the present azimuthally and radially asymmetric core, the concept of core sectors is introduced. A core sector is simply a portion of the core which is bounded by a locus of points of a first and a second radius which form an annular region in the waveguide. Each of the radii are different one from another and are less than or equal to the core radius. The remaining boundaries of a sector are two planes oriented at an angle with respect to each other and each containing the waveguide fiber centerline. A change in refractive index along a line within a sector means the refractive index is different between at least two points along the line.

DEFINITIONS

The following definitions are in accord with common usage in the art.

- A segmented core is a core which has a particular refractive index profile over a pre-selected radius segment. A particular segment has a first and a last refractive index point. The radius from the waveguide centerline to the location of this first refractive index point is the inner radius of the core region or segment. Likewise, the radius from the waveguide centerline to the location of the last refractive index point is the outer radius of the core segment.

- The relative index, Δ , is defined by the equation, $\Delta = (n_1^2 - n_2^2)/2n_1^2$, where n_1

is the maximum refractive index of the index profile segment 1, and n_2 is a reference refractive index which is taken to be, in this application, the minimum refractive index of the clad layer. The term Δ %, which is 100 X Δ, is used in the art.

- The term refractive index profile or simply index profile is the relation between Δ % or refractive index and radius over a selected portion of the core. The term α-profile refers to a refractive index profile which follows the equation,

$n(r) = n_0 (1- \Delta[r/a]^{\alpha})$ where r is core radius, Δ is defined above, a is the last point in the profile, r is chosen to be zero at the first point of the profile, and α is an exponent which defines the profile shape. Other index profiles include a step index, a trapezoidal index and a rounded step index, in which the rounding is typically due to dopant diffusion in regions of rapid refractive index change.

SUMMARY OF THE INVENTION

In a first aspect of the invention, a single mode waveguide has a core having at least one sector. The refractive index of at least one point within the sector is different from that of at least one point outside the sector. In the case where the sector is exactly half the core, the choice of what constitutes a point inside the sector can be chosen arbitrarily without any loss of precision of definition of the profile. The core refractive index profile changes along at least a portion of one radius to provide radial asymmetry. At a pre-selected radius the core refractive index within the sector is different from that outside the sector to provide azimuthal asymmetry.

In one embodiment, the overall core has cylindrical symmetry and thus is conveniently described in cylindrical coordinates, radius r, azimuth angle φ, and centerline height z. The pre-selected radius portion, Δr along which the refractive index changes is in the range $0 < \Delta r \leq r_o$, where r_o is the core radius. The pre-selected radius at which the refractive index is different for at least two different choices of azimuth angle is within this same range.

In another embodiment the pre-selected radius portion is a segment defined as $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 < r_o$.

In yet another embodiment, the refractive index changes along any or all radii within a sector, in which the sector has included angle φ greater than zero but less than or equal to 180 °.

In another embodiment the radius portion is in the range $0 < \Delta r \leq r_o$, and the azimuth angle φ and height z have any value provided the coordinate point (r, φ, z) is in the core region.

Further embodiments of the invention include those in which the number of sectors and the angular and radial size of the sectors are specified and the functional relationship between radius r and relative index percent Δ % is specified. Examples of the functional relationships are the α-profile, the step and rounded step index profiles, and the trapezoidal profile.

Yet further embodiments of the invention include waveguides having a segmented core and a specified number of sectors which include areas in which glass volumes of a particular size and shape have been embedded. Three and four sector embodiments having a particular core configuration and embedded portions are described below. In some embodiments, the embedded portions themselves have a segmented refractive index configuration.

In general the embodiments of this first aspect of the invention can be either single mode or multimode waveguide fibers.

A second aspect of the invention is a method of making an azimuthally and radially asymmetric waveguide fiber. The method may be employed to make either single mode or multimode waveguide fiber.

One embodiment of the method includes the steps of modifying the shape of a draw preform and then drawing the preform into a waveguide fiber having a circular cross section. The shape of the preform is thus transferred to the cylindrically symmetric features contained within the preform, specifically

the cylindrically symmetric core features. The draw preform shape may be changed by any of several methods such as etching, sawing, drilling, or grinding.

In an embodiment of the method, the preform is altered by forming holes or surface indentations therein. Subsequent drawing of the altered preform into a waveguide fiber of circular cross section causes a circularly symmetric core to become radially or azimuthally asymmetry.

In yet another embodiment of the method, two or more core preforms are fabricated and inserted into a glass tube to form a preform assembly. The waveguide fiber resulting from drawing the preform assembly has the asymmetry of the assembly. Spacer glass particles or rods may be incorporated into the tube-core preform assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a cross sectional view of an embodiment of the waveguide or preform of the invention, having a central core design.

Fig. 1B is the index profile taken through the 1B section of Fig. 1A

Fig. 1C is the index profile taken through the 1C section of Fig. 1A.

Fig. 1D is a cross sectional view of an embodiment of the waveguide or preform of the invention having a central core design.

Fig. 1E is the index profile taken through the 1E section of Fig. 1D.

Fig. 1F is the index profile taken through the 1F section of Fig. 1D.

Fig. 1G is a cross sectional view of an embodiment of the waveguide or preform of the invention, having an embedded core design.

Fig. 2A is a cross sectional view of an embodiment of the waveguide or preform having an embedded core design.

Fig. 2B is the index profile taken through the 2B section of Fig. 2A.

Fig. 2C is a cross sectional view of an embodiment of the waveguide or preform having an embedded core design.

Fig. 2D is the index profile taken through the 2D section of Fig. 2C.

Fig. 2E is a cross sectional view of an mbodiment of the waveguide or preform having an embedded core design.

Fig 2F is a cross sectional view of an embodiment of the waveguide or preform having an embedded core design.

Fig. 3. is a cross sectional view of the novel waveguide or preform containing voids.

Fig. 4A & B, and 4C & D show, in cross section, the transfer of the preform outer shape to the core after drawing.

Fig. 5A & B illustrate, in cross section, the affect on the core shape of preform voids.

Fig. 6A & B, and 7A & B illustrate a cross section of a preform core and tube assembly and the resulting waveguide after drawing the assembly.

Fig. 8A & B illustrate a cross section of a notched segmented core preform and the resulting waveguide after draw.

DETAILED DESCRIPTION OF THE INVENTION

Th core 2 of Fig. 1A is made azimuthally asymmetric by indentations 4. In this illustration of the novel preform or waveguide fiber, the indentations comprise the same material as that of the clad layer 6. The perpendicular sections through the core, 1B and 1C are set forth in Fig. 1B and Fig. 1C, respectively and, show the azimuthal variation in width of the step index profile. This particular profile is symmetric in the radial direction.

The preform or waveguide core of Fig. 1D is both radially and azimuthally asymmetric. In this illustration of the novel waveguide or preform, the core is divided into four sectors. Each of the two diagonally opposed sectors, 8 and 10 are mirror images of each other as is shown by the sections 1F and 1E taken through the core. In Fig. 1E, the radial dependence of the 1E section is shown as 16, a rounded step or an α-profile. In Fig. 1F, the profile 18 of the 1F section is a step index profile. The clad portions 12 and 14 may comprise any material having a refractive index lower than that of the adjacent core region. That is, the composition of the clad layer is generally limited only by the condition that the core clad structure guide rather than radiate light launched into the waveguide.

Fig. 1G is an example of a more complex structure in accord with the novel preform and waveguide. In this illustration waveguide core or core preform 20 comprises a segmented core having central region 22, and adjoining annular regions 28, 24, and 26. Each region is characterized by a respective relative refractive index Δ %, an index profile and an area determined by radii 32, 34, 36, 38 and 40. For example, central region 22 and annular region 24 may comprise respective germanium doped silica glasses and annular regions 28 and 26 may comprise silica and the relative sizes of the areas may be as shown. The asymmetry is introduced into the core preform by embedded glass volumes 30, which in general have a refractive index different from that of either annular segment 24 or 26 contacted by the glass volumes 30.

The glass volumes 30 can be form d by sawing or grinding, for example, followed by filling of the volumes with a glass by any of a number of means

including deposition. The distribution of light energy carried by core 20 will be determined by the relative refractive indexes and sizes of the segments

22, 28, 24, 26, and 30. The functional properties of the waveguide are determined by the distribution of light energy across the core preform or core 20.

In another embodiment of the novel preform or waveguide, the core is comprised of a matrix glass 50 having embedded glass volumes 42, 44, and 48 as illustrated in Fig. 2A. The glass volumes extend from end to end of the preform or the waveguide drawn from the preform. The clad glass layer 52 surrounds the core 50. The refractive index of core glass 50 is higher than that of clad layer 52. Section 2B through one of the embedded volumes is shown in Fig. 2B as a step index profile. The sizes of cross sectional area of the embedded glass volumes 42, 44 and 48 can be the same or different and a number of relative orientations relative to the clad glass layer are possible.

The structure of Fig. 2A can made by drilling a preform, smoothing the walls of the resulting holes, and filling the holes with glass powder or rods. As an alternative, the core can be formed of rods which are then inserted into a holding tube, either with or without the use of spacer glass rods or particles. The need for a holding tube can be eliminated by welding the rods together using appropriate glass spacer material. The overclad layer can be deposited over the welded assembly of rods or can be fabricated as a tube which is shrunk onto the assembly before or during draw.

Another embodiment which includes a matrix glass and a plurality of embedded glass volumes is shown in Fig. 2C. Here the gross structure of waveguide 54 is similar to that of Fig. 2A, except that the embedded glass volumes 56, 58 and 60 each have a segmented core refractive index profile. An example of the segmented core profile is shown in Fig. 2D, which is the cross section through one of the embedded volumes in which a central region of relatively high Δ % is surrounded by two annular regions, 62 and 64. In the illustration, the first annulus 62 is lower in Δ % than the second annulus 64. It is understood that each of the segments may have a radial dependence selected from a plurality of possibilities, such as an α-profile or a rounded step

profile, and the relative Δ %'s of the segments can be adjusted to provide different waveguide functional properties.

The methods of making the preform or waveguide of Fig. 2C are essentially identical to the method of making the preform or waveguide of Fig. 2A.

Two additional embodiments of this preform or waveguide type are illustrated in Figs. 2E & 2F. The embedded glass volumes 66, 68, and 70 in Fig. 2E have a rectangular cross section and are arranged substantially at the apexes of an equilateral triangle. Other arrangements of the embedded glass volumes are contemplated such as arrangement along a diameter of the core region. The core region 72 can comprise a number of shapes and compositions. In the simple example illustrated in Fig. 2E, the core glass 72 is a step index profile and, as is required to guide light, has a higher refractive index than at least a portion of the clad layer 74.

In Fig. 2F a configuration comprising five embedded glass volumes is illustrated. Here, four glass volumes of diamond cross section 76, 78, 80 and 82 are symmetrically arranged about a circular central core region 84. It is evident that numerous variations of this design are possible. For example the refractive indexes of the embedded volumes 76, 78, 80, 82, and 84 can each have a different relative index as compared to that of the core 86.

As is shown in Fig. 3, the embedded volumes 88 in a preform or a waveguide can be voids. A waveguide having elongated voids along the long axis can be made by forming elongated voids, for example, by drilling or etching, in a core or draw preform. The index of the core glass 90 is necessarily different from that of the voids, thus providing an asymmetrical core region. In the case in which Fig. 3 represents a draw preform, the voids may be collapsed during the draw process to produce an asymmetric core. The shape of the core region after collapse of the voids is determined by the relative viscosity of core material 90 and clad layer material 92. Control of the relative viscosity of the glasses is maintained by control of temperature gradient in the portion of the preform being drawn. The relative viscosity also depends up n core and clad glass composition.

Figs. 4A and 4B illustrate the transfer of a preform shape, 98 in Fig. 4A, from the clad layer portion 94 of the preform, to the core portion 102 in Fig. 4B of a waveguide 100 drawn from preform 98. The transfer occurs as shown in Figs. 4A and 4B when the initial symmetry of the preform core 96 is the same as the symmetry of the waveguide clad layer 104. Cylindrical symmetry is shown because this is the symmetry most compatible with current preform fabrication and draw processes. Other symmetries are possible, for example, by partial transfer of the preform shape to the waveguide core shape. i.e., th final shape of the waveguide departs from cylindrical symmetry.

A cross section of a segmented core preform having a square shape is shown in Fig. 4C. After heating and drawing the preform into a cylindrical waveguide, the segmented core, 106 in Fig. 4D, takes on square shape due to the viscous flow of the core material which takes place to accommodate the cylindrically shaped surface of the clad layer.

In an analogous manner, the preform of Fig. 5A, having core 110, clad layer 112 and elongated voids 108, will produce an asymmetric core when drawn into a cylindrically shaped waveguide. However, in this case the preform is cylindrical, and the movement of the core material is due to the filling of the voids during draw. As long as the preform shape is preserved as the preform is drawn into a waveguide, the core must distort, i.e., become asymmetric, to fill the voids.

Example

A preform of the type shown in Fig. 5A was made using the outside vapor deposition process. The core region 110 was germanium doped silica and the clad layer 112 was silica. Voids 108 were formed in the preform by drilling followed by smoothing of the walls of the void using an etching solution. The preform was drawn into a waveguide fiber having the zero dispersion wavelength in the 1500 nm operation window, i.e., the waveguide was dispersion shifted. The waveguide had an unusually large mode field diameter of 10.4 μm as compared to mode field diameters in the range of 7 μm to 8 μm for dispersion shifted waveguides having an azimuthally symmetric core.

A method of making an asymmetric core is illustrated in Figs. 6A and 6B. Segmented core preforms 114, 116 and 118 are fabricated using any of several known methods including, outside vapor deposition, axial vapor deposition, plasma deposition, or modified chemical vapor deposition. The core preforms are inserted into tube 122 where they are held in place by spacer rods 120. The rods may be made of silica, doped silica or the like. If needed, a clad layer 124 may be deposited on the tube. The preform assembly may now be drawn into a waveguide fiber having cores 130, 132, and 134 embedded in core glass 128 and surrounded by clad glass layer 126 as shown in Fig. 6B. The assembly as shown in Fig. 6A may be drawn directly. As an alternative, the deposited clad layer may be consolidated prior to draw. In addition, before clad deposition, the tube, core preform and spacer rod assembly may be heated sufficiently to soften the surfaces thereof to cause them to adhere to each other, thereby forming a more stable structure for use in the overclad or draw process.

The method of making an asymmetric core shown in Figs. 7A and 7B is closely related to that illustrated in Figs. 6A and 6B. In Fig. 7A the core is bounded by annulus 136 which serves to better contain light propagating in step index core preforms 138, 140, and 142. As described above, spacer rods or glass powder may be used to stabilize the relative positions of the core preforms within the annulus. The assembly of core preforms, optional spacer material, annulus and overclad material may be drawn directly or first consolidated and then drawn. The resulting waveguide fiber is shown in Fig. 7B.

A final example of a method of forming an asymmetric core is shown in Figs. 8A and 8B. In Fig. 8A a preform has a segmented core having central region 144, first annular region 146, and second annular region 148. The preform has been ground or sawed or the like to form notches 152. The notches may be empty or filled with material 150 which is a material different in composition from that of clad layer 154. The preform assembly is drawn to form a waveguide having an asymmetric core as shown in Fig. 8B. Here again

the assembly may be drawn directly or deposition, consolidation, or tacking steps may be carried out before draw to hold the parts of the preform in proper relative registration.

Although particular embodiments of the invention have been disclosed and described herein, the invention is nonetheless limited only by the following claims.

We claim:

1. A single mode optical waveguide fiber having a radial and azimuthal asymmetric core comprising:

a core region in contact with a surrounding clad layer, at least a portion of the core region having a refractive index which is greater than the refractive index of at least a portion of the clad layer;

the waveguide having a centerline parallel to the long dimension of the waveguide, and the waveguide having at least one core sector bounded by a first and a second plane, and a segment of the core region periphery intersected by the first and the second plane, wherein the first and second planes each contain the centerline and form at the centerline an included angle $\varphi \leq 180^{\circ}$,

in which, the core refractive index changes along at least a portion, Δr, of a pre-selected radius extending perpendicular to and outward from the centerline, and,

the core refractive index at least at a point at a pre-selected radius inside the at least one core sector has a value different from the core refractive index value at least at a point at the pre-selected radius outside the at least one core sector.

2. The single mode waveguide of claim 1, in which, the core region has a cylindrical shape and a point in the core region has cylindrical coordinates, radius r, azimuth angle φ, and centerline height z, and the radius of the core region is $r = r_o$, and the pre-selected portion of the radius is in the range $0 < \Delta r \leq r_o$.

3. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius is the segment $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 < r_o$.

4. The single mode waveguide of either claim 2 or claim 3 in which the pre-selected portion of the radius lies along any radius in at least one sector having included angle $0 < \varphi \leq 180^{\circ}$.

5. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius Δr is in the range $0 < \Delta r \leq r_o$, the azimuth angle of the radius is in the

range $0 \leq \varphi \leq 360$ °, and the radius is drawn from any point z along the centerline.

6. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius is the segment $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 \leq r_o$, the azimuth angle of the radius containing the segment is in the range $0 \leq \varphi \leq 360$ °, and the radius containing the segment is drawn from any point z along the centerline.

7. The single mode waveguide of claim 2, in which, the core has 4 sectors of equal volume numbered consecutively from 1 to 4 in a counter-clockwise azimuth direction, and the boundary planes of each sector have an included angle of 90 °, and sectors 1 and 3 have a radial change in refractive index defined by a function f(r), and sectors 2 and 4 have a radial change in refractive index defined by a function g(r).

8. The single mode waveguide of claim 7, in which, g(r) is a step index and f(r) is an α- profile.

9. The single mode waveguide of claim 2, in which, the core has 4 sectors of equal volume, the bounding planes of each sector having an included angle of 90 °, the refractive index profile of each sector having a central portion of radius r_c and relative index Δ_c, extending between the planes bounding the sector,

a first annular region in contact with the central portion, having outer radius r_1, relative index Δ_1, and extending between the planes bounding the sector,

a second annular region in contact with the first annular region, having outer radius r_2, relative index Δ_2, and extending between the planes bounding the sector,

a third annular region in contact with the second annular region, having outer radius r_3, relative index Δ_3, and extending between the planes bounding the sector,

a first volume of constant refractive index embedded in the core of the first sector and bounded on a first part of its surface by a part of the first plane

bounding the sector and bounded on a second part of its surface by a part of the first, second, and third annular regions,

a second volume of constant refractive index embedded in the core of the first sector and bounded on a first part of its surface by a part of the second plane bounding the sector and bounded on a second part of its surface by a part of the first, second, and third annular regions, wherein,

each of the remaining three sectors contain embedded volumes having surfaces bounded in a way corresponding to the volumes embedded in the first sector, wherein, the relative indexes and the radii follow the inequalities, $0 \leq r_c < r_1 < r_2 < r_3 \leq r_o$ and $\Delta_c \geq \Delta_2 > \Delta_1 \geq \Delta_3$.

10. The single mode waveguide of claim 2, in which the core has three sectors, and each sector comprises a volume of a first glass of constant refractive index embedded in a volume of a second glass of constant refractive index, in which the refractive index of the first glass is greater than the refractive index of the second glass.

11. The single mode waveguide of claim 10 in which each of the first glass volumes is an elongated body having its long axis aligned parallel to the centerline, wherein the perpendicular cross section of the elongated body is selected from the group consisting of a circle, an ellipse, and a parallelogram.

12. The single mode waveguide of claim 2, in which the core has three sectors, and each sector contains an elongated glass volume having a central portion, a first annular portion surrounding and in contact with the central portion, and at least one additional annular portion in contact with the annular portion which the at least one additional annular portion surrounds, wherein the long axis of each of the elongated structures is parallel to the centerline.

13. The single mode waveguide of claim 12 in which the central portion is a cylinder having radius r_c and relative index Δ_c, and the annular regions are tubes having respective outer radii r_i and relative index Δ_i, where i = 1...n, and n is the number of annular portions, in which Δ_i for i = an even number is greater than Δ_i for i equal to an odd number.

14. The single mode waveguide of claim 2 in which the core has four sectors each sector comprising a first glass volume having relative index Δ_1, and embedded in the first glass volume of each sector is an elongated volume of a second glass having relative index Δ_2, wherein the respective elongated volumes are arranged symmetrically about the centerline.

15. A method of making a radially and azimuthally asymmetric single mode or multimode optical waveguide fiber comprising the steps:

a) fabricating a single mode or multimode optical waveguide fiber preform having a long axis, a core, and a clad, wherein any cross section of the preform, perpendicular to the long axis, is circular;

b) grinding, sawing, or otherwise removing peripheral portions of the preform to alter the preform surface such that any cross section of the preform taken perpendicular to the long axis has a shape which is essentially the same as the shape of any other cross section of the preform perpendicular to the long axis;

c) heating and drawing the preform along its long axis into a waveguide fiber having a core, a long axis and a circular cross section perpendicular to the long axis at any point along the long axis, to provide a waveguide fiber core having the shape of the altered preform.

16. The method of claim 15 in which step b) includes forming one or more indentations in the preform surface.

17. The method of claim 16 in which the fabricating step a) includes the step of fabricating a segmented core preform comprising, a central core region and at least one annular portion surrounding and in contact with the central core region, wherein the relative refractive index of the central region is different from the relative refractive index of the annular portion and the one or more indentations penetrate at least into the annular portion.

18. A method of making a radially and azimuthally asymmetric single mode or multimode waveguide comprising the steps:

a) fabricating an optical waveguide fiber preform having a long axis, a core, and a clad, wherein any cross section of the preform, perpendicular to the long axis, is circular;

b) drilling or grinding or otherwise producing in the waveguide preform one or more holes which extend along the long axis;

c) heating and drawing the preform along its long axis into a waveguide fiber having a core, a long axis and a circular cross section perpendicular to the long axis at any point along the long axis, to provide a radially and azimuthally asymmetric waveguide fiber core.

19. A method of making a radially and azimuthally asymmetric single mode or multimode optical waveguide fiber comprising the steps:

a) fabricating at least two waveguide fiber core preforms each having a long axis;

b) inserting the at least two core preforms into a tube made of clad glass to form a core preform-tube assembly having a long axis, wherein interstitial voids are formed among the boundaries of the at least two core preforms and the inside of the tube;;

c) heating and drawing the assembly along its long axis into a waveguide fiber having a core, a long axis and a circular cross section perpendicular to the long axis at any point along the long axis, to provide a waveguide fiber having a radially and azimuthally asymmetric core.

20. The method of claim 19 further including the step, prior to step c), of inserting in the interstices formed among the at least two core preforms and the tube, clad glass having a shape selected from the group consisting of particles, rods, and microspheres.

21. The method of claim 19 wherein the fabricating step a) includes the step of fabricating a segmented core preform comprising, a central core region and at least one annular portion surrounding and in contact with the central core region, wherein the relative refractive index of the central region is different from the relative refractive index of the annular portion.

22. A multimode optical waveguide fiber having a radial and azimuthal asymmetric core comprising:

a core region in contact with a surrounding clad layer, at least a portion of the core region having a refractive index which is greater than the refractive index of at least a portion of the clad layer;

the waveguide having a centerline parallel to the long dimension of the waveguide, and the waveguide having four core sectors each bounded by a first and a second plane, and a segment of the core region periphery intersected by the first and the second plane, wherein the first and second planes each contain the centerline and form at the centerline an included angle $\varphi \leq 180^{\circ}$, wherein,

the core region is of cylindrical shape and a point in the core region has cylindrical coordinates, radius r, azimuth angle φ, and centerline height z, and the radius of the core region is $r = r_o$, and the refractive index changes along a radius portion Δr in the range $0 < \underline{\Delta} r \leq r_o$, wherein,

the four core sectors have equal volume numbered consecutively from 1 to 4 in a counter-clockwise azimuth direction, and the boundary planes of each sector having an included angle of 90°, and sectors 1 and 3 have a radial change in refractive index defined by a function f(r), and sectors 2 and 4 have a radial change in refractive index defined by a function g(r).

23. The waveguide of claim 22, in which, g(r) is a step index and f(r) is an α-profile.

24. The waveguide of claim 22, in which, the four core sectors are of equal volume, the bounding planes of each sector having an included angle of 90°, the refractive index profile of each sector having a central portion of radius r_c and relative index Δ_c, extending between the planes bounding the sector,

a first annular region in contact with the central portion, having outer radius r_1, relative index Δ_1, and extending between the planes bounding the sector,

a second annular region in contact with the first annular region, having outer radius r_2, relative index Δ_2, and extending between the planes bounding the sector,

a third annular region in contact with the second annular region, having outer radius r_3, relative index Δ_3, and extending between the planes bounding the sector,

a first volume of constant refractive index embedded in the core of the first sector and bounded on a first part of its surface by a part of the first plane bounding the sector and bounded on a second part of its surface by a part of the first, second, and third annular regions,

a second volume of constant refractive index embedded in the core of the first sector and bounded on a first part of its surface by a part of the second plane bounding the sector and bounded on a second part of its surface by a part of the first, second, and third annular regions, wherein,

each of the remaining three sectors contain embedded volumes having surfaces bounded in a way corresponding to the volumes embedded in the first sector, wherein, the relative indexes and the radii follow the inequalities, $0 \leq r_c < r_1 < r_2 < r_3 \leq r_o$ and $\Delta_c \geq \Delta_2 > \Delta_1 \geq \Delta_3$.

25. The waveguide of claim 22 in which the four core sectors each comprise a first glass volume having relative index Δ_1, and embedded in the first glass volume of each sector is an elongated volume of a second glass having relative index Δ_2, wherein the respective elongated volumes are arranged symmetrically about the centerline.

26. A multimode optical waveguide fiber having a radial and azimuthal asymmetric core comprising:

a core region in contact with a surrounding clad layer, at least a portion of the core region having a refractive index which is greater than the refractive index of at least a portion of the clad layer;

the waveguide having a centerline parallel to the long dimension of the waveguide, and the waveguide having four core sectors each bounded by a first and a second plane, and a segment of the core region periphery intersected by the first and the second plane, wherein the first and second planes each contain the centerline and form at the centerline an included angle $\varphi \leq 180^{\circ}$, wherein,

the core region is of cylindrical shape and a point in the core region has cylindrical coordinates, radius r, azimuth angle φ, and centerline height z, and

the radius of the core region is $r = r_o$, and the refractive index changes along a radius portion Δr in the range $0 < \Delta r \leq r_o$, wherein,

the core has three sectors, and each sector comprises a volume of a first glass of constant refractive index embedded in a volume of a second glass of constant refractive index, in which the refractive index of the first glass is greater than the refractive index of the second glass.

27. The waveguide of claim 26 in which each of the first glass volumes is an elongated body having its long axis aligned parallel to the centerline, wherein the perpendicular cross section of the elongated body is selected from the group consisting of a circle, an ellipse, and a parallelogram.

28. The waveguide of claim 26, in which the three core sectors each contain an elongated glass volume having a central portion, a first annular portion surrounding and in contact with the central portion, and at least one additional annular portion in contact with the annular portion which the at least one additional annular portion surrounds, wherein the long axis of each of the elongated structures is parallel to the centerline.

29. The waveguide of claim 28 in which the central portion is a cylinder having radius r_c and relative index Δ_c, and the annular regions are tubes having respective outer radii r_i and relative index Δ_i, where $i = 1 \ldots n$, and n is the number of annular portions, in which Δ_i for i = an even number is greater than Δ_i for i equal to an odd number.

Fig. 1 a

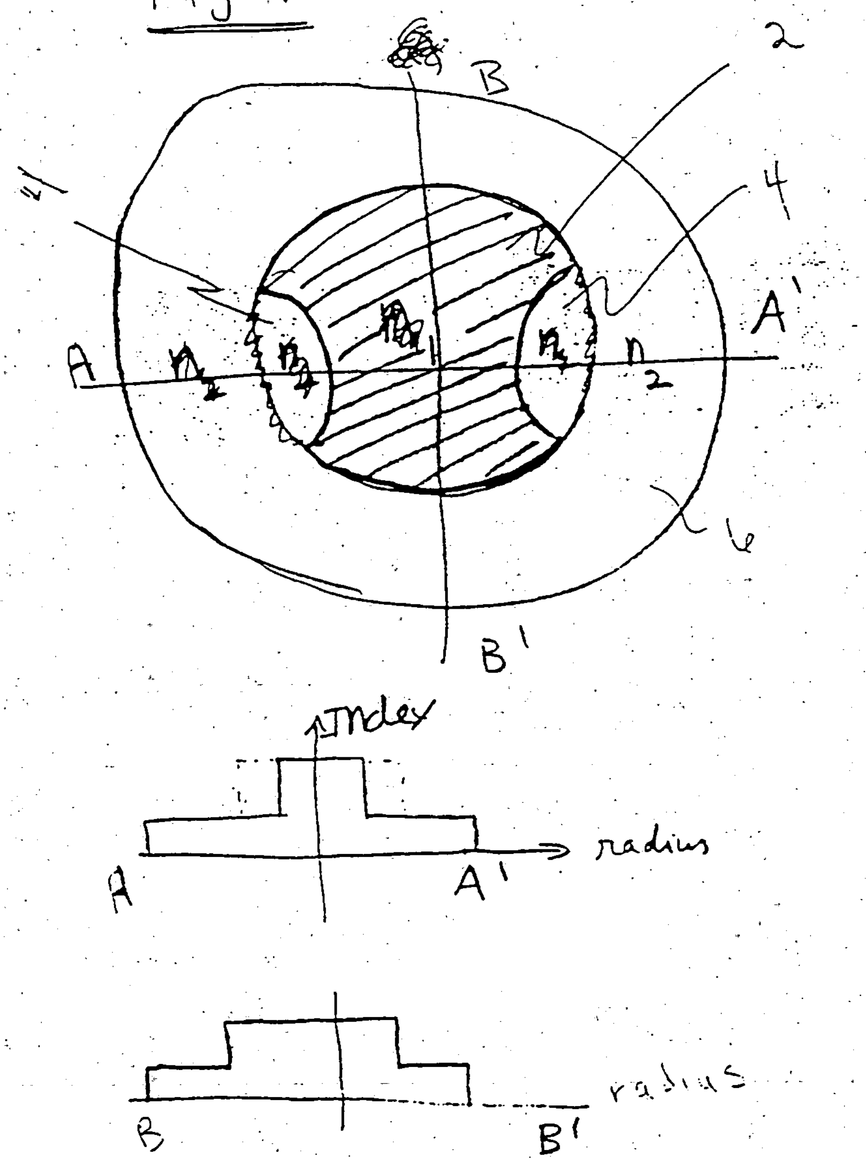
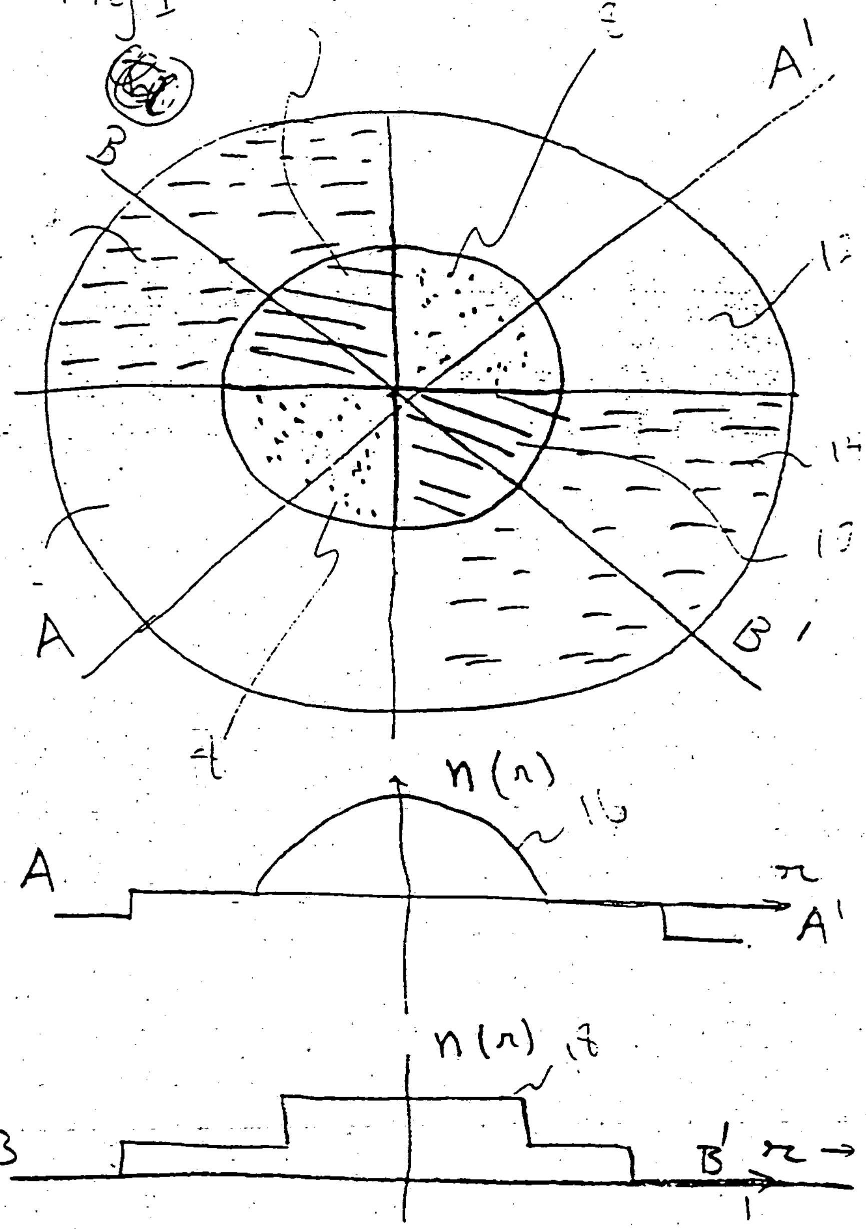


Fig 1b



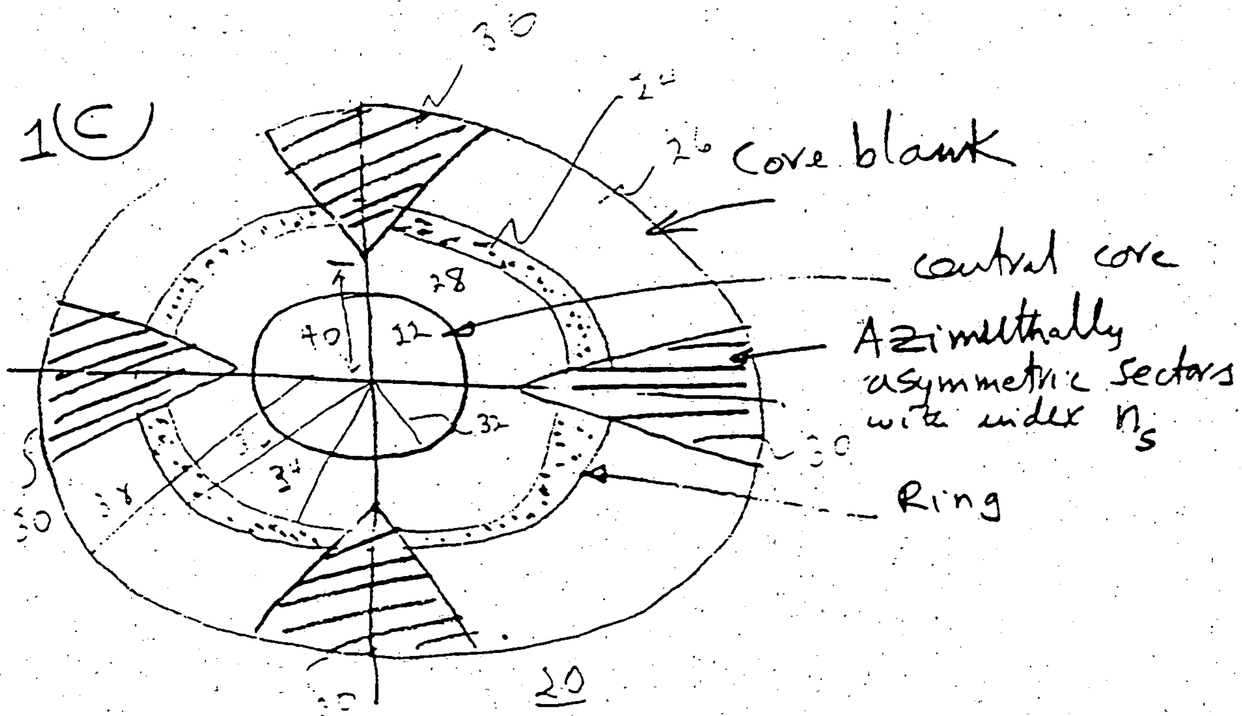
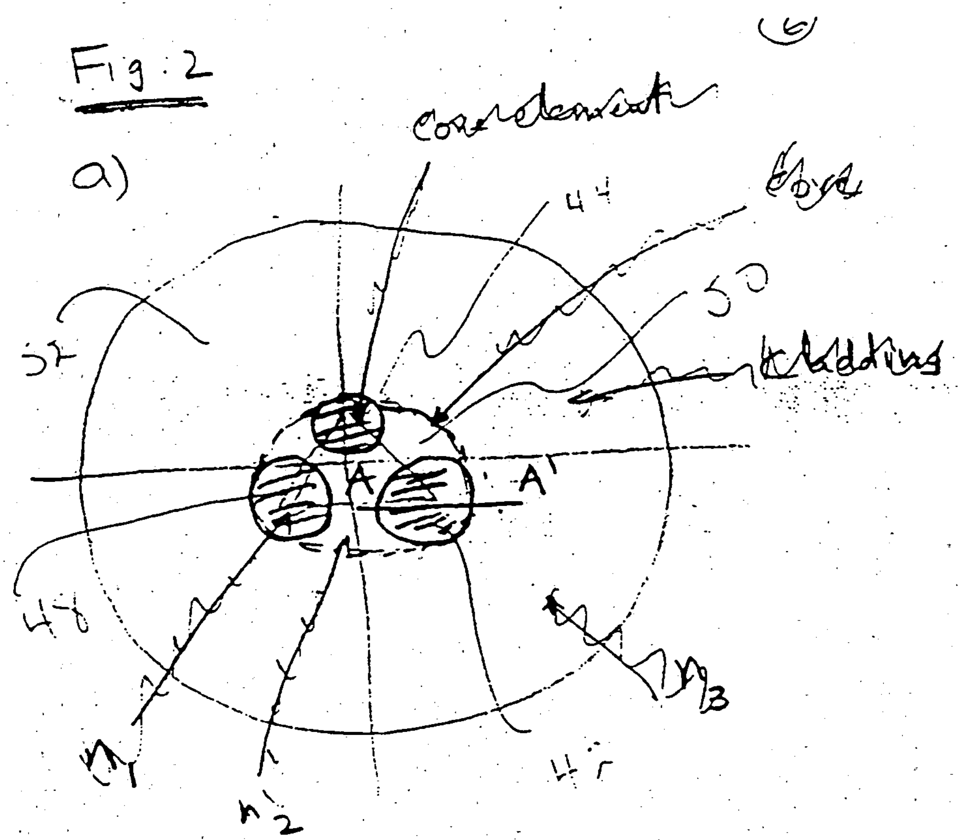

1(C)
30
24
26
core blank
central core
28
40
22
Azimuthally
asymmetric sectors
with index n_s
32
30
34
38
Ring
50
30
20

Fig. 2

a)



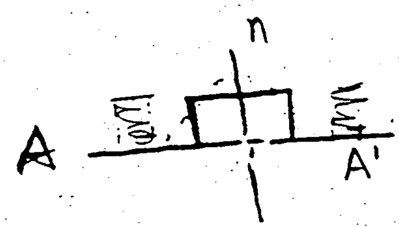


Fig 2 b

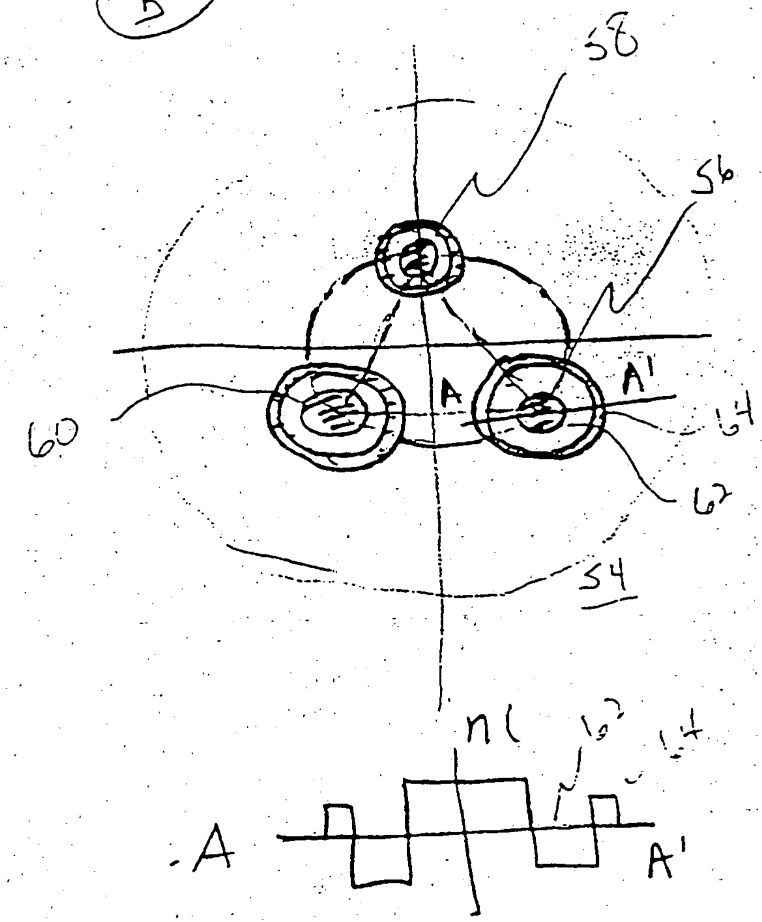


Fig 2 c

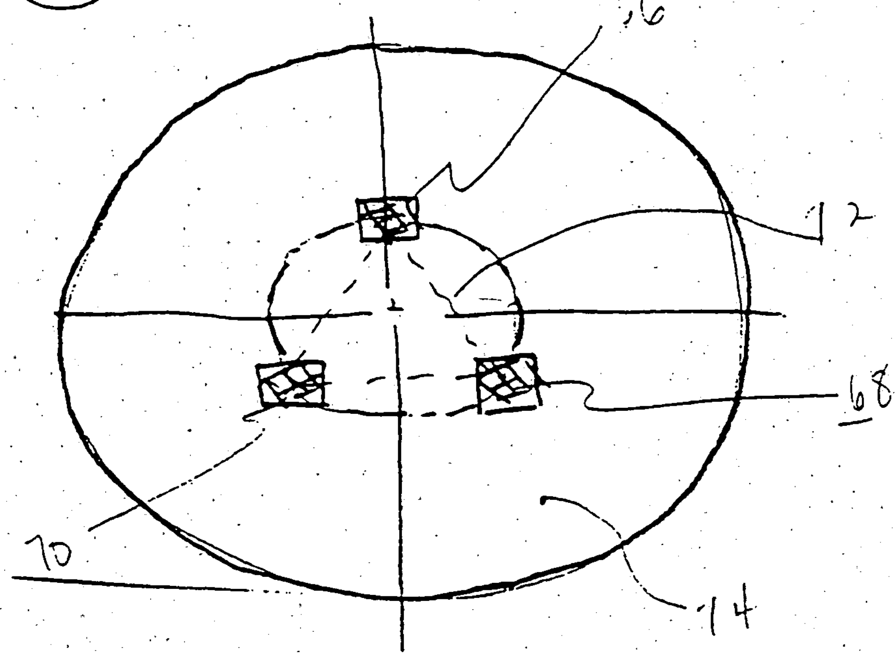


Fig 2 d

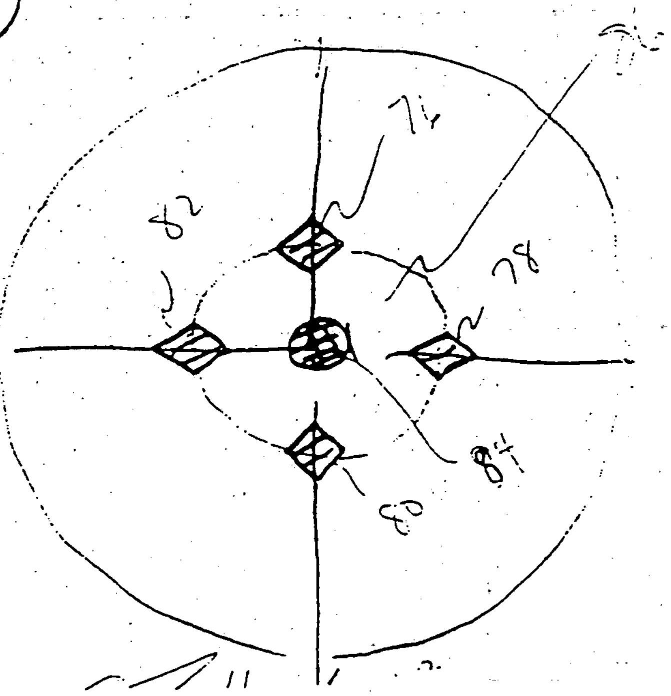
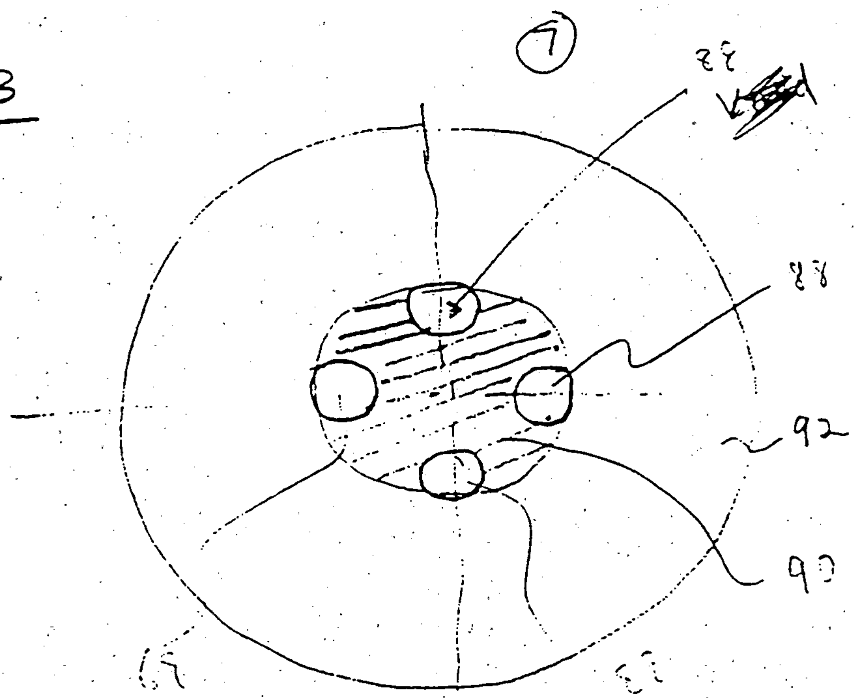
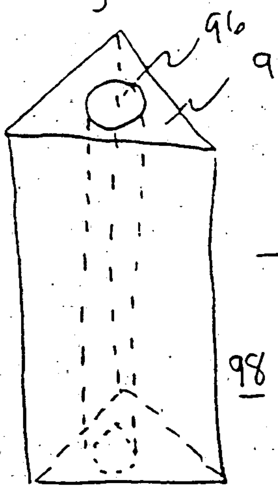


Fig 3



Method.

Fig. 4a



4b

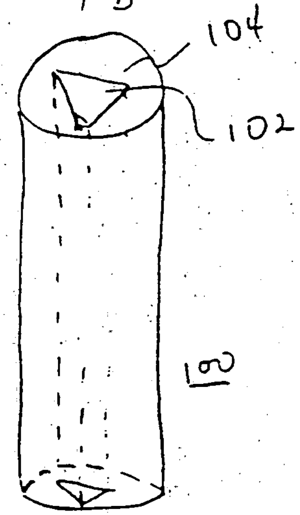
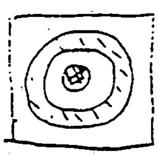
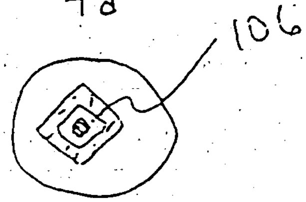


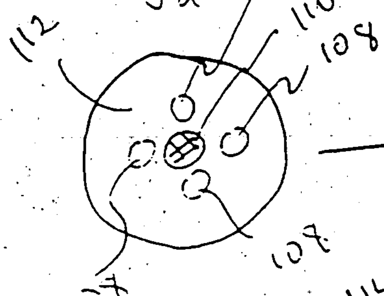
Fig 4c



4d



5a



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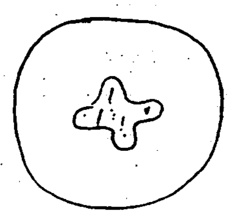
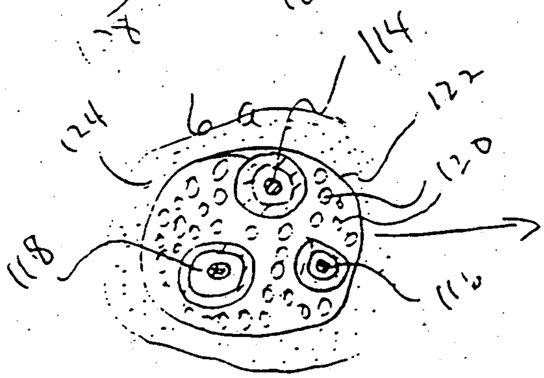


6a



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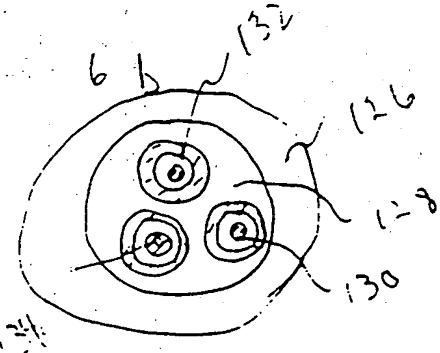
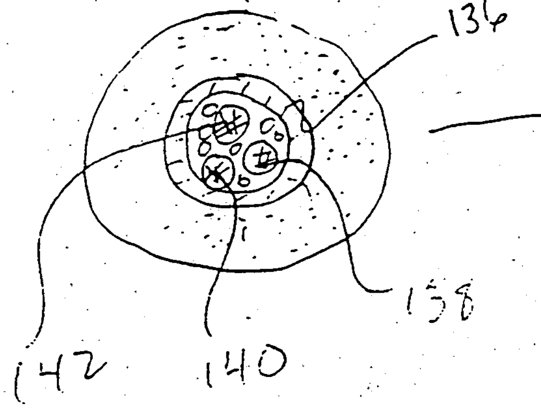


7a



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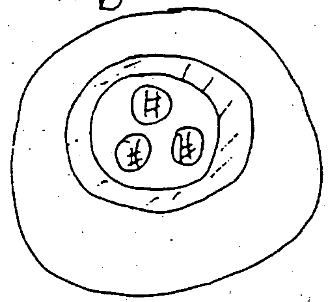
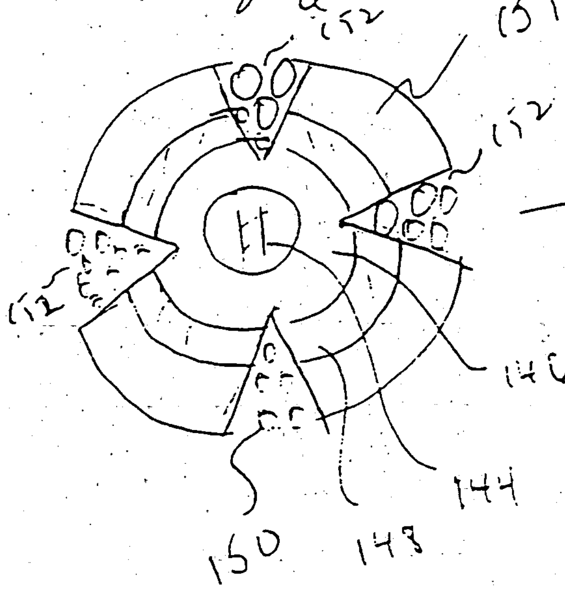
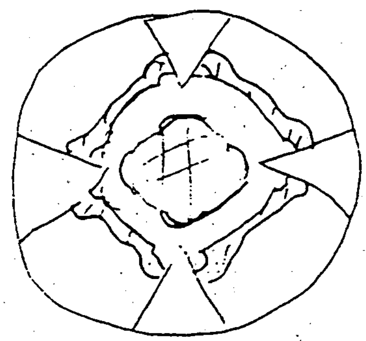


8a



8b



PATENT COOPERATION TREATY

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

To: WILLIAM J. CHERVENAK
PATENT DEPARTMENT
SP TI 3-1
CORNING INCORPORATED
CORNING NY 14831

PCT

NOTIFICATION OF TRANSMITTAL OF INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Rule 71.1)

Date of Mailing *(day/month/year)*	24 OCT 2000
Applicant's or agent's file reference: BHAGAVATULA 32-16	**IMPORTANT NOTIFICATION**

International application No.	International filing date *(day/month/year)*	Priority Date *(day/month/year)*
PCT/US99/18933	20 AUGUST 1999	09 SEPTEMBER 1998

Applicant
CORNING INCORPORATED

1. The applicant is hereby notified that this International Preliminary Examining Authority transmits herewith the international preliminary examination report and its annexes, if any, established on the international application.

2. A copy of the report and its annexes, if any, is being transmitted to the International Bureau for communication to all the elected Offices.

3. Where required by any of the elected Offices, the International Bureau will prepare an English translation of the report (but not of any annexes) and will transmit such translation to those Offices.

4. **REMINDER**

   The applicant must enter the national phase before each elected Office by performing certain acts (filing translations and paying national fees) within 30 months from the priority date (or later in some Offices)(Article 39(1))(see also the reminder sent by the International Bureau with Form PCT/IB/301).

   Where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary examination report. It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned.

   For further details on the applicable time limits and requirements of the elected Offices, see Volume II of the PCT Applicant's Guide.

Name and mailing address of the IPEA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	JULIANA KANG
Facsimile No. (703) 305-3230	Telephone No. (703) 305-6259

Form PCT/IPEA/416 (July 1992) ★

30 Oct 00

PA NT COOPERATION TREAT

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

To:

Assistant Commissioner for Patents
United States Patent and Trademark Office
Box PCT
Washington, D.C.20231
ETATS-UNIS D'AMERIQUE

in its capacity as elected Office

Date of mailing (day/month/year) 20 April 2000 (20.04.00)	
International application No. PCT/US99/18933	**Applicant's or agent's file reference** Bhagavatula
International filing date (day/month/year) 20 August 1999 (20.08.99)	**Priority date** (day/month/year) 09 September 1998 (09.09.98)
Applicant BHAGAVATULA, Venkata, A. et al	

1. The designated Office is hereby notified of its election made:

   [X] in the demand filed with the International Preliminary Examining Authority on:

   04 February 2000 (04.02.00)

   [ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was

   [ ] was not

   made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer C. Villet Telephone No.: (41-22) 338.83.38

PATENT COOPERATION TREATY

From the
INTERNATIONAL PRELIMINARY EXAMINING AUTHORITY

To: WILLIAM J. CHERVENAK
PATENT DEPARTMENT
SP TI 3-1
CORNING INCORPORATED
CORNING NY 14831

WJC

DOCKETED
MAY 31 2000
RCS
KAW

PCT WRITTEN OPINION

(PCT Rule 66)

26 July 2000

Date of Mailing (*day/month/year*)	26 MAY 2000
REPLY DUE	within TWO months from the above date of mailing

Applicant's or agent's file reference		
BHAGAVATULA		
International application No.	International filing date (*day/month/year*)	Priority date (*day/month/year*)
PCT/US99/18933	20 AUGUST 1999	09 SEPTEMBER 1998

International Patent Classification (IPC) or both national classification and IPC
IPC(7) G02B 6/18, 6/22 and US Cl.: 385/123, 124, 126, 127;

Applicant
CORNING INCORPORATED

1. This written opinion is the first (first, etc.) drawn by this International Preliminary Examining Authority.

2. This opinion contains indications relating to the following items:

- I [X] Basis of the opinion
- II [ ] Priority
- III [X] Non-establishment of opinion with regard to novelty, inventive step or industrial applicability
- IV [ ] Lack of unity of invention
- V [X] Reasoned statement under Rule 66.2(a)(ii) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- VI [ ] Certain documents cited
- VII [ ] Certain defects in the international application
- VIII [ ] Certain observations on the international application

CDJ
MAY 31 2000

3. The applicant is hereby invited to reply to this opinion.

When? See the time limit indicated above. ~~The applicant may, before the expiration of that time limit, request this Authority to grant an extension, see Rule 66.2(d).~~

How? By submitting a written reply, accompanied, where appropriate, by amendments, according to Rule 66.3. For the form and the language of the amendments, see Rules 66.8 and 66.9.

Also For an additional opportunity to submit amendments, see Rule 66.4.
For the examiner's obligation to consider amendments and/or arguments, see Rule 66.4 *bis*.
For an informal communication with the examiner, see Rule 66.6.

If no reply is filed, the international preliminary examination report will be established on the basis of this opinion.

4. The final date by which the international preliminary examination report must be established according to Rule 69.2 is: 09 JANUARY 2001.

Name and mailing address of the IPEA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Juliana K. Kang
Facsimile No. (703) 305-3230	Telephone No. (703) 305-6259

WRITTEN OPINION

International application No.

PCT/US99/18933

I. Basis of the opinion

1. With regard to the **elements** of the international application:*

[X] the international application as originally filed

[X] the description:
pages 1-11, as originally filed
pages NONE, filed with the demand
pages NONE, filed with the letter of ______

[X] the claims:
pages 12-19, as originally filed
pages NONE, as amended (together with any statement) under Article 19
pages NONE, filed with the demand
pages NONE, filed with the letter of ______

[X] the drawings:
pages 1-8, as originally filed
pages NONE, filed with the demand
pages NONE, filed with the letter of ______

[X] the sequence listing part of the description:
pages NONE, as originally filed
pages NONE, filed with the demand
pages NONE, filed with the letter of ______

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.
These elements were available or furnished to this Authority in the following language ______ which is:

[ ] the language of a translation furnished for the purposes of international search (under Rule 23.1(b)).

[ ] the language of publication of the international application (under Rule 48.3(b)).

[ ] the language of the translation furnished for the purposes of international preliminary examination (under Rules 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the written opinion was drawn on the basis of the sequence listing:

[ ] contained in the international application in printed form.

[ ] filed together with the international application in computer readable form.

[ ] furnished subsequently to this Authority in written form.

[ ] furnished subsequently to this Authority in computer readable form.

[ ] The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.

[ ] The statement that the information recorded in computer readable form is identical to the writen sequence listing has been furnished.

4. [X] The amendments have resulted in the cancellation of:

[X] the description, pages NONE

[X] the claims, Nos. NONE

[X] the drawings, sheets/~~fig~~ NONE

5. [ ] This opinion has been drawn as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).

* *Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this opinion as "originally filed".*

WRITTEN OPINION

International application No.
PCT/US99/18933

III. Non-establishment of opinion with regard to novelty, inventive step and industrial applicability

1. The questions whether the claimed invention appears to be novel, to involve an inventive step (to be non obvious), or to be industrially applicable have not been and will not be examined in respect of:

☐ the entire international application.

☒ claims Nos. 15-29

because:

☐ the said international application, or the said claim Nos. _ relate to the following subject matter which does not require international preliminary examination *(specify)*:

☐ the description, claims or drawings *(indicate particular elements below)* or said claims Nos. _ are so unclear that no meaningful opinion could be formed *(specify)*:

☐ the claims, or said claims Nos. _ are so inadequately supported by the description that no meaningful opinion could be formed.

☒ no international search report has been established for said claims Nos. 15-29.

2. A written opinion cannot be drawn due to the failure of the nucleotide and/or amino acid sequence listing to comply with the standard provided for in Annex C of the Administrative Instructions:

☐ the written form has not been furnished or does not comply with the standard.

☐ the computer readable form has not been furnished or does not comply with the standard.

WRITTEN OPINION

International application No.
PCT/US99/18933

V. Reasoned statement under Rule 66.2(a)(ii) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. statement

Novelty (N)	Claims	8-14	YES
	Claims	1-7	NO
Inventive Step (IS)	Claims	8	YES
	Claims	1-7, 9-14	NO
Industrial Applicability (IA)	Claims	1-14	YES
	Claims	NONE	NO

2. citations and explanations

1. Claims 1-7 lack novelty under PCT Article 33(2) as being anticipated by Bassett (WO 89/11109).
Bassett discloses a single mode optical waveguide fiber comprising four segmented core region with a cladding surrounding the core region with the cladding having a refractive index less than the core region. The core is formed with its cross-section with four regions, each of which has an average refractive index grater that of the surrounding portions of the core.

2. Claims 9-14 lack inventive step under PCT Article 33(3) as being obvious over Bassett in view of Someda (U.S. Patent 4,758,066).
As described above, Bassett discloses a single mode circularly birefringent optical fiber having a four sector central core and a surrounding cladding. However, Bassett does not teach the sectors being disposed in annular matter. Someda teaches a circularly birefringent optical fiber with three annular sectors of core with the refractive indices vary in the radial direction. Thus it would not involve an invention step for one with ordinary skill in the art to use Someda's annular sectors of core in Bassett since both are from the same field of endeavor.

3. Claim 8 meets the criteria set out in PCT Article 33(2)-(4), because the prior art does not teach or fairly suggest the single mode waveguide with four core sectors wherein the sectors 1 and 3 have a radial change in refractive index of an a-profile function and the sectors 2 and 4 have a radial change in refractive index of a step index function.

-------------------- NEW CITATIONS --------------------

US 4,748,066 A (Someda) 19 July 1988, see abstract, column 2 line 53-column 3 lines 19.

WRITTEN OPINION

International application No.
PCT/US99/18933

Supplemental Box
(To be used when the space in any of the preceding boxes is not sufficient)

Continuation of: Boxes I - VIII

Sheet 10

TIME LIMIT:

The time limit set for response to a Written Opinion may not be extended. 37 CFR 1.484(d). Any response received after the expiration of the time limit set in the Written Opinion will not be considered in preparing the International Preliminary Examination Report.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

REC'D 02 NOV 2000
WIPO PCT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference BHAGAVATULA	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/US99/18933	International filing date (*day/month/year*) 20 AUGUST 1999	Priority date (*day/month/year*) 09 SEPTEMBER 1998
International Patent Classification (IPC) or national classification and IPC IPC(7): G02B 6/18, 6/22 and US Cl.: 385/123, 124, 126, 127		
Applicant CORNING INCORPORATED		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 4 sheets.

   [✓] This report is also accompanied by ANNEXES, i.e., sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority. (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of ~~X~~ 3 sheets.

3. This report contains indications relating to the following items:

   - I [X] Basis of the report
   - II [ ] Priority
   - III [ ] Non-establishment of report with regard to novelty, inventive step or industrial applicability
   - IV [ ] Lack of unity of invention
   - V [X] Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - VI [ ] Certain documents cited
   - VII [ ] Certain defects in the international application
   - VIII [ ] Certain observations on the international application

Date of submission of the demand	Date of completion of this report
04 FEBRUARY 2000	28 SEPTEMBER 2000
Name and mailing address of the IPEA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer JULIANA KANG Telephone No. (703) 305-6259

Form PCT/IPEA/409 (cover sheet) (July 1998) *

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.
PCT/US99/18933

I. Basis of the report

1. With regard to the **elements** of the international application:*

- [ ] the international application as originally filed
- [X] the description:
  - pages (See Attached), as originally filed
  - pages ______, filed with the demand
  - pages ______, filed with the letter of ______
- [X] the claims:
  - pages (See Attached), as originally filed
  - pages ______, as amended (together with any statement) under Article 19
  - pages ______, filed with the demand
  - pages ______, filed with the letter of ______
- [X] the drawings:
  - pages (See Attached), as originally filed
  - pages ______, filed with the demand
  - pages ______, filed with the letter of ______
- [X] the sequence listing part of the description:
  - pages (See Attached), as originally filed
  - pages ______, filed with the demand
  - pages ______, filed with the letter of ______

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.
These elements were available or furnished to this Authority in the following language ______ which is:

- [ ] the language of a translation furnished for the purposes of international search (under Rule 23.1(b)).
- [ ] the language of publication of the international application (under Rule 48.3(b)).
- [ ] the language of the translation furnished for the purposes of international preliminary examination (under Rules 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- [ ] contained in the international application in printed form.
- [ ] filed together with the international application in computer readable form.
- [ ] furnished subsequently to this Authority in written form.
- [ ] furnished subsequently to this Authority in computer readable form.
- [ ] The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- [ ] The statement that the information recorded in computer readable form is identical to the writen sequence listing has been furnished.

4. [X] The amendments have resulted in the cancellation of:
   - [X] the description, pages NONE
   - [X] the claims, Nos. 5-8, 14
   - [X] the drawings, sheets/~~fig~~ NONE

5. [X] This report has been drawn as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).**

* *Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17).*

***Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.*

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.
PCT/US99/18933

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. statement

Novelty (N)	Claims	1-4, 9-13	YES
	Claims	NONE	NO
Inventive Step (IS)	Claims	1-4, 9-13	YES
	Claims	NONE	NO
Industrial Applicability (IA)	Claims	1-4, 9-13	YES
	Claims	NONE	NO

2. citations and explanations (Rule 70.7)

Claims 1-4 and 9-13 meets the criteria set out in PCT Article 33(2)-(4), because the prior art does not teach or fairly suggest single mode waveguide having a radial and azimuthal asymmetric core comprising a core divided into four segments wherein one of diagonally opposed sectors have a radial change in refractive index of an a-profile function and the other diagonally opposed sectors have a radial change in refractive index of a step index function as set forth in claim 1.

-------------------- NEW CITATIONS --------------------
NONE

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No.

PCT/US99/18933

Supplemental Box
(To be used when the space in any of the preceding boxes is not sufficient)

Continuation of: Boxes I - VIII

Sheet 10

I. BASIS OF REPORT:

This report has been drawn on the basis of the description.
page(s) 1-11. as originally filed.
page(s) NONE, filed with the demand.
and additional amendments:
NONE

This report has been drawn on the basis of the claims,
page(s) 14, 16-19, as originally filed.
page(s) NONE, as amended under Article 19.
page(s) NONE, filed with the demand.
and additional amendments:
Pages 12, 13, and 15 filed with the letter of 19 JUL 2000

This report has been drawn on the basis of the drawings.
page(s) 1-8, as originally filed.
page(s) NONE, filed with the demand.
and additional amendments:
NONE

This report has been drawn on the basis of the sequence listing part of the description:
page(s) NONE, as originally filed.
pages(s) NONE, filed with the demand.
and additional amendments:
NONE

5. (Some) amendments are considered to go beyond the disclosure as filed:
NONE

REPLACED BY ART 34 AMDT

We claim:

1. A single mode optical waveguide fiber having a radial and azimuthal asymmetric core comprising:

a core region in contact with a surrounding clad layer, at least a portion of the core region having a refractive index which is greater than the refractive index of at least a portion of the clad layer;

the waveguide having a centerline parallel to the long dimension of the waveguide, and the waveguide having at least one core sector bounded by a first and a second plane, and a segment of the core region periphery intersected by the first and the second plane, wherein the first and second planes each contain the centerline and form at the centerline an included angle $\varphi \leq 180°$,

in which, the core refractive index changes along at least a portion, Δr, of a pre-selected radius extending perpendicular to and outward from the centerline, and,

the core refractive index at least at a point at a pre-selected radius inside the at least one core sector has a value different from the core refractive index value at least at a point at the pre-selected radius outside the at least one core sector.

2. The single mode waveguide of claim 1, in which, the core region has a cylindrical shape and a point in the core region has cylindrical coordinates, radius r, azimuth angle φ, and centerline height z, and the radius of the core region is $r = r_o$, and the pre-selected portion of the radius is in the range $0 < \Delta r \leq r_o$.

3. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius is the segment $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 < r_o$.

4. The single mode waveguide of either claim 2 or claim 3 in which the pre-selected portion of the radius lies along any radius in at least one sector having included angle $0 < \varphi \leq 180°$.

5. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius Δr is in the range $0 < \Delta r \leq r_o$, the azimuth angle of the radius is in the

range $0 \leq \varphi \leq 360\,°$, and the radius is drawn from any point z along the centerline.

6. The single mode waveguide of claim 2, in which, the pre-selected portion of the radius is the segment $\Delta r = r_2 - r_1$, where, $0 \leq r_1 < r_2$ and $r_2 \leq r_o$, the azimuth angle of the radius containing the segment is in the range $0 \leq \varphi \leq 360\,°$, and the radius containing the segment is drawn from any point z along the centerline.

7. The single mode waveguide of claim 2, in which, the core has 4 sectors of equal volume numbered consecutively from 1 to 4 in a counter-clockwise azimuth direction, and the boundary planes of each sector have an included angle of 90 °, and sectors 1 and 3 have a radial change in refractive index defined by a function f(r), and sectors 2 and 4 have a radial change in refractive index defined by a function g(r).

8. The single mode waveguide of claim 7, in which, g(r) is a step index and f(r) is an α- profile.

9. The single mode waveguide of claim 2, in which, the core has 4 sectors of equal volume, the bounding planes of each sector having an included angle of 90 °, the refractive index profile of each sector having a central portion of radius r_c and relative index Δ_c, extending between the planes bounding the sector,

a first annular region in contact with the central portion, having outer radius r_1, relative index Δ_1, and extending between the planes bounding the sector,

a second annular region in contact with the first annular region, having outer radius r_2, relative index Δ_2, and extending between the planes bounding the sector,

a third annular region in contact with the second annular region, having outer radius r_3, relative index Δ_3, and extending between the planes bounding the sector,

a first volume of constant refractive index embedded in the core of the first sector and bounded on a first part of its surface by a part of the first plane

14. The single mode waveguide of claim 2 in which the core has four sectors each sector comprising a first glass volume having relative index Δ_1, and embedded in the first glass volume of each sector is an elongated volume of a second glass having relative index Δ_2, wherein the respective elongated volumes are arranged symmetrically about the centerline.

15. A method of making a radially and azimuthally asymmetric single mode or multimode optical waveguide fiber comprising the steps:

a) fabricating a single mode or multimode optical waveguide fiber preform having a long axis, a core, and a clad, wherein any cross section of the preform, perpendicular to the long axis, is circular;

b) grinding, sawing, or otherwise removing peripheral portions of the preform to alter the preform surface such that any cross section of the preform taken perpendicular to the long axis has a shape which is essentially the same as the shape of any other cross section of the preform perpendicular to the long axis;

c) heating and drawing the preform along its long axis into a waveguide fiber having a core, a long axis and a circular cross section perpendicular to the long axis at any point along the long axis, to provide a waveguide fiber core having the shape of the altered preform.

16. The method of claim 15 in which step b) includes forming one or more indentations in the preform surface.

17. The method of claim 16 in which the fabricating step a) includes the step of fabricating a segmented core preform comprising, a central core region and at least one annular portion surrounding and in contact with the central core region, wherein the relative refractive index of the central region is different from the relative refractive index of the annular portion and the one or more indentations penetrate at least into the annular portion.

18. A method of making a radially and azimuthally asymmetric single mode or multimode waveguide comprising the steps:

a) fabricating an optical waveguide fiber preform having a long axis, a core, and a clad, wherein any cross section of the preform, perpendicular to the long axis, is circular;

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/18933

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/17 G02B6/22 C03B37/012

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B C03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 014, no. 180 (C-0708), 11 April 1990 (1990-04-11) & JP 02 026847 A (SUMITOMO ELECTRIC IND LTD), 29 January 1990 (1990-01-29)	1-8
Y	abstract	9
X	WO 89 11109 A (UNIV SYDNEY) 16 November 1989 (1989-11-16) page 2, line 25 -page 4, line 2; figures 2A,2B	1-6, 10-14
X	PATENT ABSTRACTS OF JAPAN vol. 009, no. 161 (P-370), 5 July 1985 (1985-07-05) & JP 60 035702 A (FURUKAWA DENKI KOGYO KK), 23 February 1985 (1985-02-23) abstract	1-6

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 November 1999	18.05.00

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lord, R

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/18933

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 006, no. 092 (P-119), 29 May 1982 (1982-05-29) & JP 57 026810 A (NIPPON TELEGR & TELEPH CORP), 13 February 1982 (1982-02-13) abstract ---	1-8
Y	PATENT ABSTRACTS OF JAPAN vol. 012, no. 288 (P-741), 8 August 1988 (1988-08-08) & JP 63 065408 A (FUJITSU LTD), 24 March 1988 (1988-03-24) abstract -----	9

3

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT	.ernational application No. PCT/US 99/ 18933

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sh et)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

B x II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

1. Claims: 1-14

   Single-mode optical fibre with radially and azimuthally asymmetric core, characterised by the form of the core profile

2. Claims: 15-21

   Methods of fabricating radially and azimuthally asymmetric fibres characterised by the technique for introducing the core asymmetry

3. Claims: 18-29

   Optical fibre with radially and azimuthally asymmetric core characterised in that it is multimode

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/18933

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 02026847 A	29-01-1990	NONE	
WO 8911109 A	16-11-1989	NONE	
JP 60035702 A	23-02-1985	NONE	
JP 57026810 A	13-02-1982	JP 1206799 C	11-05-1984
		JP 58031565 B	07-07-1983
JP 63065408 A	24-03-1988	JP 2016871 C	19-02-1996
		JP 7015529 B	22-02-1995

Annex to form PCT/ISA/206
COMMUNICATION RELATING TO THE RESULTS OF THE PARTIAL INTERNATIONAL SEARCH

International Application No
PCT/US 99/18933

1. The present communication is an Annex to the invitation to pay additional fees (Form PCT/ISA/206). It shows the results of the international search established on the parts of the international application which relate to the invention first mentioned in claims Nos.:
1-14

2. This communication is not the international search report which will be established according to Article 18 and Rule 43.

3. If the applicant does not pay any additional search fees, the information appearing in this communication will be considered as the result of the international search and will be included as such in the international search report.

4. If the applicant pays additional fees, the international search report will contain both the information appearing in this communication and the results of the international search on other parts of the international application for which such fees will have been paid.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	PATENT ABSTRACTS OF JAPAN vol. 014, no. 180 (C-0708), 11 April 1990 (1990-04-11) & JP 02 026847 A (SUMITOMO ELECTRIC IND LTD), 29 January 1990 (1990-01-29) abstract ---	1-8 9
X	WO 89 11109 A (UNIV SYDNEY) 16 November 1989 (1989-11-16) page 2, line 25 -page 4, line 2; figures 2A,2B ---	1-6, 10-14
X	PATENT ABSTRACTS OF JAPAN vol. 009, no. 161 (P-370), 5 July 1985 (1985-07-05) & JP 60 035702 A (FURUKAWA DENKI KOGYO KK), 23 February 1985 (1985-02-23) abstract ---	1-6
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[X] Further documents are listed in the continuation of box C.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

3

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	PATENT ABSTRACTS OF JAPAN vol. 012, no. 288 (P-741), 8 August 1988 (1988-08-08) & JP 63 065408 A (FUJITSU LTD), 24 March 1988 (1988-03-24) abstract -----	9

3

[redacted]t Family Annex

Informa[redacted]patent family members

[redacted] Application No
PC[redacted]S 99/18933

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
JP 02026847	A	29-01-1990	NONE			
WO 8911109	A	16-11-1989	NONE			
JP 60035702	A	23-02-1985	NONE			
JP 57026810	A	13-02-1982	JP	1206799	C	11-05-1984
			JP	58031565	B	07-07-1983
JP 63065408	A	24-03-1988	JP	2016871	C	19-02-1996
			JP	7015529	B	22-02-1995